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Modification of the magnetic properties of longitudinal thin-film media by ion-beam irradiation

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ABSTRACT

The modification of conventional longitudinal recording media by ion-beam irradiation is of both scientific and technological interest. In particular, patterning by irradiation through a stencil mask at the 50 nm length scale may fulfill the promise of a commercially viable patterned media architecture. In this context, the magnetic properties and microstructural evolution of high-coercivity longitudinal thin film media were investigated after ion-beam irradiation. TRIM simulations were used to calculate the depth profiles and damage distributions as a function of energy and dose for carbon, nitrogen, and chromium ions and three different media (C, Cr, no capping layer). Corresponding implantations were carried out and hysteresis curves were measured using a vibrating sample magnetometer (VSM). Using chromium ion implantation at 20 keV, both remanence and coercivity were reduced to zero, i.e., rendering the ferromagnetic thin film paramagnetic, at doses as low as 1×10^{16} cm^{-2}. For C^+ implantation at 20 keV, remanence and coercivity were also reduced to varying extent up to doses of 5×10^{16} cm^{-2} after which further irradiation had no effect. Slight decreases in remanence and coercivity were observed for 20 keV N_2^+ irradiation. XRD measurements indicate that the hexagonal cobalt alloy phase remains intact after irradiation. The physical and magnetic domain structures at the surface were assessed by atomic force and magnetic force microscopy. Combined with the development of a suitable stencil mask, such chromium ion implantation can be used to develop a viable patterned media with nanoscale dimensions, consisting of locally defined ferromagnetic and paramagnetic regions. This work is in progress.

INTRODUCTION

Improvements in the ability to carefully control the magnetic properties of thin films have made significant contributions to the recent 60% growth rate in the areal bit density of magnetic recording media. Historically, these improvements have been associated with reductions in grain size and advances in grain isolation (made necessary by statistical noise constraints requiring a certain number of grains per bit). The superparamagnetic effect, a grain size limit that renders magnetic moments unstable with respect to thermal fluctuations, represents a fundamental roadblock to the current regime of media development. Since the magnetic properties of interest in such recording systems occur in the near-surface region, ion beam processing may be an appropriate means of asserting yet further control over the important physical, chemical and magnetic microstructures of these films. Baglin et al.[1] have previously reported the loss of uniaxial anisotropy and an increase in coercivity in Permalloy thin films with irradiation by a number of ion species at MeV energies.

Modifying the properties of ferromagnetic thin films is both of scientific and technological interest. If an ion-beam process that induces a ferromagnetic-to-paramagnetic transition ($M_s \rightarrow 0$) can be identified at room temperature, patterning through a stencil mask at the 50 nm length scale may fulfill the promise of a commercially viable patterned media architecture. For example, Chappert et al.[2] and Weller et al.[3] have reported local variations in coercivity and easy magnetization axis in Co/Pt multilayers via light ion irradiation near the MeV energy range.

In this research, we investigate the effect of Cr^+, C^+, and N_2^+ irradiation on the magnetic properties of a commercial CoCrPt thin-film media. Our approach is to introduce structural and chemical changes by systematically varying the ion species and qualities of the protective cap layer. Protective overcoats in commercial media range in thickness up to 250 Å. Controlling the amount of energy absorbed by cap layer atoms will change the ion range and damage profiles. Furthermore, a certain number of these carbon and chromium atoms will recoil, coming to rest within the CoCrPt layer. The saturation magnetization of CoCr-alloys is well known to decrease with Cr enrichment, approaching zero at roughly 25 at% Cr [4]. Diffusion of carbon atoms into CoCr-alloys has also been shown to decrease M_s [5]. Both species reduce the Curie temperature of cobalt alloys. It is reasonable to expect that C^+ and Cr^+ implantation into CoCrPt thin films will result in similar compositional effects. Nitrogen ions, in the form of the relatively inert N_2^+, should introduce large numbers of target displacements through collision cascade dynamics. The resulting expansion of the lattice may weaken the exchange interaction by increasing the ratio of interatomic separation to 3*d*-orbital radius, as predicted by the Bethe-Slater curve [6-8].

EXPERIMENT

Commercial thin-film recording media, prepared by dc magnetron sputtering on aluminum disk substrates, were obtained courtesy of Seagate Recording Media (Fremont, CA). The complete film structure was $Al/Ni_{77}P_{23}$(>0.5 μm)/$Cr_{83}Ta_{17}$(320 Å)/$Co_{72}Cr_{18}Pt_{10}$(100 Å), as determined by Rutherford backscattering spectrometry. Thin cap layers of Cr and C defined additional variations of the media based on the film structure mentioned above. These films were machined and backside thinned to produce 8 mm disk samples. The in-plane and plane normal magnetic hysteresis curves were characterized along the circumferential orientation of the original disk by using a vibrating sample magnetometer (VSM) with saturating fields of ±14 kOe. The structural properties of the as grown films were determined using XRD. TRIM[9] simulations were used to model and optimize the irradiation process for C^+, N_2^+ and Cr^+ irradiation in the C/Cr capped and uncapped media. Corresponding implantations were carried out at 20 keV incident energy; structural and magnetic properties as a function of ion dose were characterized by XRD and VSM. Atomic force (AFM) and magnetic force microscopy (MFM) was performed on a Digital Instruments Nanoscope Dimension 3000 Scanning Probe Microscope in tapping LiftMode®. The probe tip was etched Si tip sputter coated with a CoCr thin film.

RESULTS

Figure 1 shows the TRIM concentration and damage event profiles as a function of depth for 20 keV C^+, N_2^+ and Cr^+ implantation in the Cr capped media. The composition and thickness of the cap layers influence these distributions by absorbing energy from energetic ions. The TRIM results were used to determine optimum irradiation conditions and cap layer thickness based on the twin goals of delivering a peak concentration of either ions or damage events within the magnetic layer. The concentration and damage profiles of chromium and nitrogen ions, respectively, peak within the magnetic layer. In order to study all ion species at constant incident energy, larger doses were selected for C^+ implantation. TRIM was also used to relate the physics of ion-solid interactions to observed changes in magnetic properties.

As determined by VSM, the coercivity (H_c) and saturation magnetization (M_s) as a function of ion species, dose, and cap layer are plotted in Figure 2 for incident energies of 20 keV. The magnetization was completely in-plane. Both M_s and H_c decreased with dose in all cases, in contrast with the results of Baglin et al.[1], who observed increasing H_c. The rate of decline is quite different for each respective ion species. Chromium ions caused the most dramatic change in magnetic properties; both H_c and M_s were reduced to zero (within instrument sensitivity) at doses as low as 10^{16} Cr^+ cm^{-2}. Carbon ions achieved similar, although incomplete, reductions in magnetic properties but at higher doses. These observations are consistent with the chemical effects expected from adding C or Cr into a CoCr-alloy. The much weaker response to nitrogen ions suggests that ion-induced lattice disruption does not play a dominant role here.

From Figure 2 it is also apparent that cap layers play an important role in the evolution of magnetic properties with dose. Both coercivity and saturation magnetization decline more rapidly in capped film structures. This behavior is most striking for C^+ and Cr^+ irradiated systems and is perhaps explained by the transfer of energy from incident ions to the cap layer, leading to shallower depth profiles which retain more implanted species within the magnetically active $Co_{72}Cr_{18}Pt_{10}$ layer. Ion-beam mixing might also

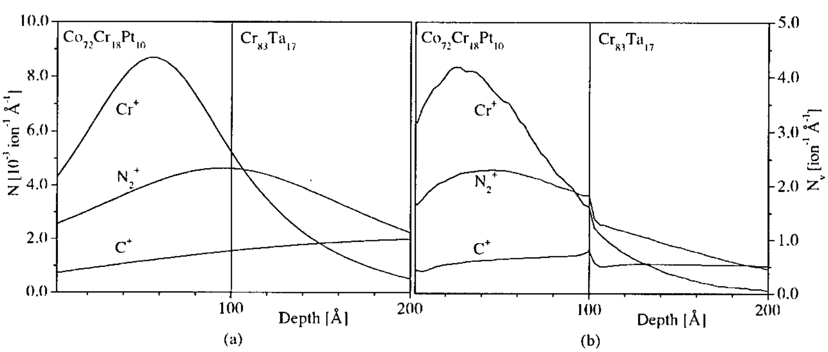

Figure 1. TRIM simulations of (a) projected range and (b) damage distributions for 20 keV ion implantation in CoCrPt/Cr_{cap} media (cap layer not shown).

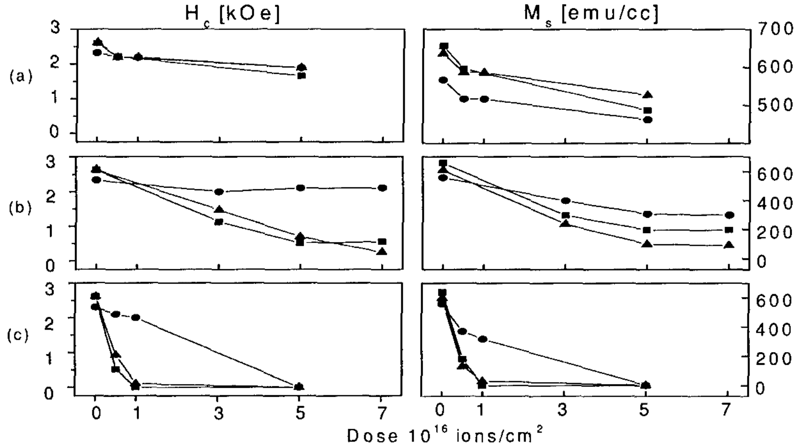

Figure 2. Magnetic properties of 20 keV (a) N_2^+, (b) C^+ and (c) Cr^+ irradiated films in uncapped (circles), C_{cap}, (squares), and Cr_{cap} (triangles) media.

lead to more rapid accumulation of Cr and/or C as recoiling cap layer atoms near the interface come rest within the magnetic layer.

It is noteworthy that M_s and H_c evolve in a similar manner with dose of C^+, N_2^+, and Cr^+; moreover, the parallel decline of these properties suggests the uniaxial magnetocrystalline anisotropy constant K_u of the CoCrPt phase declines even more rapidly than M_s. While M_s and K_u are fundamental material properties, H_c is microstructure-sensitive, scaling as $H_c \propto 2K_u / M_s$ [10]. For chromium ion implanted films, the implied decrease in K_u is agrees with Iwasaki et al. [11], who reported the intrinsic magnetocrystalline anisotropy constant in sputtered CoCr thin films declined with Cr content from 37×10^5 erg cm^{-3} (10 at% Cr) to 1.3×10^5 erg cm^{-3} (25 at% Cr).

X-ray diffraction scans for equivalent doses of 20 keV C^+, N_2^+, and Cr^+ irradiated films with Cr cap layers are shown in Figure 3, demonstrating the CoCrPt phase generally retains $(11\bar{2}0)$ texture without change in lattice spacing. These scans prove that the observed changes in magnetic properties are not due to successive removal of cap and magnetic layer by sputtering. The 0.396% compression (Cr^+ ions) and 1.67% expansion (C^+ ions) of the Cr (002) planes may be due to the respective accumulation of displacement events or carbon ions within the CrTa adhesion layer, as predicted by TRIM simulations (Figure 1).

Figure 4 shows AFM and MFM images of as grown and 20 keV 3×10^{16} Cr^+ cm^{-2} irradiated Cr_{cap} media in a remanent magnetization state. The AFM/MFM image pairs represent topographic and magnetic data taken from identical regions of the sample surface. The lines of vertical contrast in the AFM scans represent mechanical texturing along the circumferential direction of the disk. The AFM signal may be characterized by the rms surface roughness, which increases from 1.21 to 1.46 nm with implantation.

Although MFM does not directly measure the surface magnetization, the contrast, a stray field mapping above the as grown media, certainly suggests the presence of domains. Likewise, the lack of MFM contrast from the irradiated sample implies the

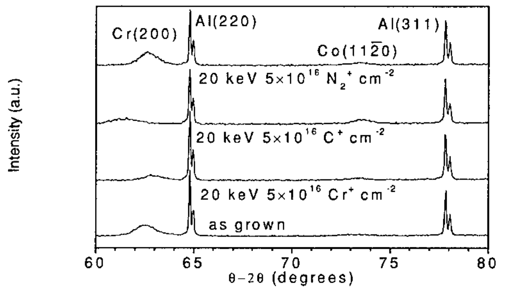

Figure 3. XRD θ-2θ scans of as grown and irradiated CoCrPt/Cr_{cap} media.

absence of magnetic moment in the near surface region. These MFM images are consistent with expectations based on earlier magnetic property measurements (Figure 2), and represent further evidence for a ferromagnetic-to-nonmagnetic transition of the CoCrPt layer.

CONCLUSIONS

The effect of 20 kV C^+, N_2^+ and Cr^+ implantation on CoCrPt ferromagnetic thin films was characterized by VSM, XRD, and scanning probe microscopy (AFM/MFM). Both M_s and H_c decreased in parallel with dose for all species. The magnitude of response

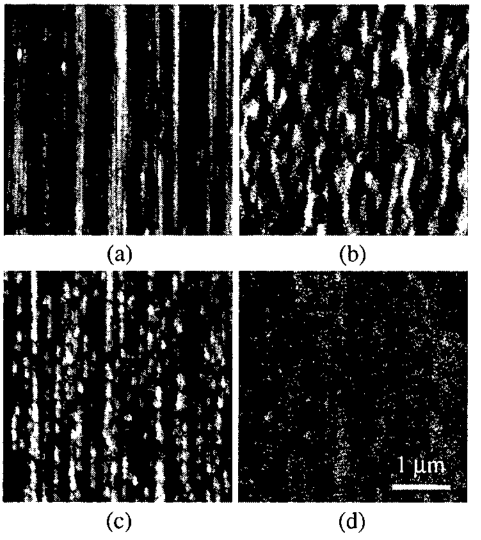

Figure 4. Scanning probe microscopy of CoCrPt/Cr_{cap} media: (a) AFM and (b) MFM of as grown samples; (c) AFM and (d) MFM of 20 kV 3×10^{16} Cr^+ cm^{-2} samples.

followed the series $N_2^+ < C^+ < Cr^+$ and was greatest for samples with protective cap layers. We have shown that, for 20 keV Cr^+ ion implantation at doses as low as 10^{16} ions cm^{-2}, the magnetization of $Co_{72}Cr_{18}Pt_{10}$ longitudinal media exhibits essentially paramagnetic behavior. The mild increase in surface roughness revealed by AFM suggests the post-irradiation surface state remains compatible with small read head-media fly heights. Although there is some evidence pointing to chemical, rather than structural, effects, TEM characterization of the physical, chemical and magnetic microstructures is required to further elucidate the mechanisms of ion-induced magnetic property changes. Combined with the development of a suitable stencil mask, such chromium implantation might be used to fabricate a viable patterned media, which would consist of locally defined regions of ferromagnetic and nonmagnetic character. This work is in progress.

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